

TITLE OF THE INVENTION

MAGNETIC MEMORY

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based upon and claims the
5 benefit of priority from the prior Japanese Patent
Applications No. 2000-227320, filed July 27, 2000; and
No. 2001-157484, filed May 25, 2001, the entire
contents of both of which are incorporated herein by
reference.

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BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a magnetic memory.

2. Description of the Related Art

A magnetoresistance effect device using a magnetic
15 film has already been used as a magnetic head or a
magnetic sensor. Moreover, it is also proposed to use
the magnetoresistance effect device as a magnetic
memory (magnetoresistance effect memory), and the like.
In the magnetic memory, a magnetic memory using a
20 ferromagnetic tunnel junction is expected to realize a
nonvolatile storage, and a writing or reading access
time less than 10 nsec, reading and writing endurance
exceeding 10^{15} times, and small cell size like DRAM.

To realize such a magnetic memory using the
25 ferromagnetic tunnel junction, a sufficient magneto-
resistance ratio is necessary. In recent years, the
magnetoresistance ratio of 20% or more has been

achieved in the ferromagnetic tunnel junction.
Therefore, expectation of realizing such a magnetic
memory is increased more and more.

For example, a ferromagnetic tunnel junction
5 obtained by forming a thin Al film having a thickness
of 0.7 nm to 2.0 nm on a ferromagnetic layer, exposing
the surface of the film to an oxygen glow electric
discharge or an oxygen gas to form a tunnel barrier
layer of Al_2O_3 , and further forming a ferromagnetic
10 layer has been proposed. According to the ferro-
magnetic tunnel junction, the magnetoresistance ratio
of 20% or more is obtained (J. Appl. Phys. 79, 4724
(1996)). Moreover, a structure of a ferromagnetic
single tunnel junction has also been proposed in which
15 one layer of a pair of ferromagnetic layers is combined
with an antiferromagnetic layer to form a magnetization
pinned layer (Jpn. Pat. Appln. KOKAI Publication
No. 10-1998).

As described above, in the ferromagnetic single
20 tunnel junction, the magnetoresistance ratio of 20% or
more can be obtained. However, as compared with
competing memories such as FeRAM and flash memory, the
magnetic memory using the ferromagnetic single tunnel
junction has a problem that power consumption on
25 writing is large.

To solve the problem, a solid magnetic memory has
been proposed in which a thin film of a high

permeability material is formed around a writing wiring
(U.S. Patent Nos. 5,659,499, 5,956,267, and 5,940,319,
and International Patent Application No. WO00/10172).

According to this magnetic memory, since the high
5 permeability film is formed around the wiring, a
current value necessary for writing information to a
magnetic recording layer can efficiently be reduced.
Moreover, according to the magnetic memory, since a
magnetic flux generated by the current does not extend
10 to the outside of the high permeable magnetic film,
even a cross talk can be inhibited.

However, in the magnetic memory disclosed in the
U.S. Patent No. 5,659,499, a magnetic field cannot
uniformly be applied to the whole recording layer of a
15 magnetoresistance effect film. Moreover, in the
magnetic memory disclosed in the U.S. Patent
Nos. 5,956,267 and 5,940,319, when a structure of the
magnetic recording layer positioned between a pair of
magnetization pinned layers like in a dual spin valve
20 type double tunnel junction as described later is used,
it is difficult to efficiently apply the magnetic field
to the magnetic recording layer. Furthermore, the
magnetic memory disclosed in the International Patent
Application No. WO00/10172 has an ideal structure for
25 applying the magnetic field to the magnetic recording
layer, but it is remarkably difficult to manufacture
the structure.

Moreover, in addition to the aforementioned ferromagnetic single tunnel junction, a ferromagnetic tunnel junction in which a magnetic particle is dispersed in a dielectric material, and a ferromagnetic double tunnel junction (continuous film) have also been proposed. Even in these ferromagnetic tunnel junctions, the magnetoresistance ratio of 20% or more is obtained (Phys. Rev. B 56(10), R5747 (1997)., Applied Magnetism Journal 23, 4-2 (1999), Appl. Phys. Lett. 73(19), 2829(1998)). Additionally, according to the ferromagnetic double tunnel junction, the magnetoresistance ratio generated by increasing a voltage value applied to the magnetic tunnel junctions can be prevented from decreasing in order to obtain a desired signal voltage value.

However, the ferromagnetic double tunnel junction also has a problem that the power consumption on writing is large similarly as the ferromagnetic single tunnel junction. Moreover, when the ferromagnetic double tunnel junction is used, the magnetic recording layer is held between a pair of tunnel barrier layers and a pair of magnetization pinned layers. Therefore, even when the method disclosed in the aforementioned U.S. patent is applied, an electric current magnetic field cannot efficiently act on the magnetic recording layer. That is, the magnetic memory using the ferromagnetic double tunnel junction has a problem that

the power consumption on writing is remarkably large.

BRIEF SUMMARY OF THE INVENTION

An object of the present invention is to provide a magnetic memory in which a power consumption on writing
5 can be reduced.

According to a first aspect of the present invention, there is provided a magnetic memory comprising first and second wirings intersecting each other and positioned apart from each other, a
10 magnetoresistance effect film positioned between the first and second wirings and comprising a magnetic recording layer configured to reverse a magnetization direction thereof by changing a direction of a magnetic field, which is generated by passing writing currents
15 through the first and second wirings, between a first direction and a second direction different from the first direction, a magnetization pinned layer configured to hold the magnetization direction thereof when the direction of the magnetic field is changed
20 between the first direction and the second direction, and a nonmagnetic layer intervening between the magnetic recording layer and the magnetization pinned layer, and a first magnetic film comprising a first portion facing the magnetoresistance effect film with
25 the first wiring interposed therebetween and a pair of second portions positioned on both sides of the first wiring and magnetically connected to the first portion,

each of the first and second portions comprising either one of a high saturation magnetization soft magnetic material containing cobalt and a metal-nonmetal nanogranular film.

5 According to a second aspect of the present invention, there is provided a magnetic memory comprising first and second wirings intersecting each other and positioned apart from each other, a magnetoresistance effect film positioned between the
10 first and second wirings and comprising a magnetic recording layer configured to reverse a magnetization direction thereof by changing a direction of a magnetic field, which is generated by passing writing currents through the first and second wirings, between a first
15 direction and a second direction different from the first direction, first and second magnetization pinned layers sandwiching the magnetic recording layer and each configured to hold a magnetization direction thereof when the direction of the magnetic field is
20 changed between the first direction and the second direction, a first nonmagnetic layer intervening between the first magnetization pinned layer and the magnetic recording layer, and a second nonmagnetic layer intervening between the second magnetization
25 pinned layer and the magnetic recording layer, and a first magnetic film comprising a first portion facing the magnetoresistance effect film with the first wiring

interposed therebetween and a pair of second portions positioned on both sides of the first wiring and magnetically connected to the first portion, each of the first and second portions comprising either one of
5 a high saturation magnetization soft magnetic material containing cobalt and a metal-nonmetal nano-granular film.

According to a third aspect of the present invention, there is provided a magnetic memory
10 comprising first and second wirings intersecting each other and positioned apart from each other, a magnetoresistance effect film positioned between the first and second wirings and comprising a magnetic recording layer configured to reverse a magnetization
15 direction thereof by changing a direction of a magnetic field, which is generated by passing writing currents through the first and second wirings, between a first direction and a second direction different from the first direction, first and second magnetization pinned
20 layers sandwiching the magnetic recording layer and each configured to hold a magnetization direction thereof when the direction of the magnetic field is changed between the first direction and the second direction, a first nonmagnetic layer intervening
25 between the first magnetization pinned layer and the magnetic recording layer, and a second nonmagnetic layer intervening between the second magnetization

pinned layer and the magnetic recording layer, and a first magnetic film comprising a first portion facing the magnetoresistance effect film with the first wiring interposed therebetween and a pair of second portions positioned on both sides of the first wiring and magnetically connected to the first portion, the second portions being in contact with one of the first and second nonmagnetic layers which is closer to the first magnetic film than the other of the first and second nonmagnetic layers.

According to a fourth aspect of the present invention, there is provided a magnetic memory comprising first and second wirings intersecting each other and positioned apart from each other, a magnetoresistance effect film positioned between the first and second wirings and comprising a magnetic recording layer configured to reverse a magnetization direction thereof by changing a direction of a magnetic field, which is generated by passing writing currents through the first and second wirings, between a first direction and a second direction different from the first direction, first and second magnetization pinned layers sandwiching the magnetic recording layer and each configured to hold a magnetization direction thereof when the direction of the magnetic field is changed between the first direction and the second direction, a first nonmagnetic layer intervening

between the first magnetization pinned layer and the magnetic recording layer, and a second nonmagnetic layer intervening between the second magnetization pinned layer and the magnetic recording layer, and a first magnetic film comprising a first portion facing the magnetoresistance effect film with the first wiring interposed therebetween and a pair of second portions positioned on both sides of the first wiring and magnetically connected to the first portion, the magnetic recording layer being positioned between the second portions.

In the first to fourth aspects of the present invention, when the current is passed through the first wiring, the first magnetic film provides a flux path for a generated magnetic force line or magnetic flux. Also, the magnetic memory according to first to fourth aspects of the present invention may have a ferromagnetic tunnel junction in which the nonmagnetic layer is a nonmagnetic tunnel layer (tunnel barrier layer), or else, may have a so-called giant magnetoresistance (GMR) effect film in which the nonmagnetic layer is not the tunnel barrier layer.

When the first to fourth aspects of the present invention define a ferromagnetic tunnel junction having a structure in which the magnetization pinned layer with the fixed magnetization direction, nonmagnetic tunnel layer, and magnetic recording layer with the

reversible magnetization direction are successively laminated, this ferromagnetic tunnel junction includes not only a ferromagnetic single tunnel junction but also a ferromagnetic multiple tunnel junction.

5 Alternatively, when the first to fourth aspects of the present invention define a ferromagnetic tunnel junction having a structure in which the first magnetization pinned layer with the fixed magnetization direction, first nonmagnetic tunnel layer, magnetic
10 recording layer with the reversible magnetization direction, second magnetization pinned layer with the fixed magnetization direction, and second nonmagnetic tunnel layer are successively laminated, this ferromagnetic tunnel junction includes a ferromagnetic
15 multiple tunnel junction.

When the magnetoresistance effect film has the first and second nonmagnetic layers, the first magnetic film can be magnetically connected to the magnetic recording layer via either nonmagnetic layer. This can
20 be realized, for example, by employing the following structure. That is, a width of the first nonmagnetic layer and magnetic recording layer are set to be larger and the width of the first magnetization pinned layer is set to be smaller with respect to a distance between
25 the surfaces of the first and second portions facing to each other. Thereby, the main surface of the first nonmagnetic layer is partially exposed in

correspondence with the first and second portions. In this case, when the exposed portions of the first nonmagnetic layer are brought in contact with the first and second portions, the magnetic film is magnetically connected to the magnetic recording layer via the first nonmagnetic layer. Therefore, the magnetic flux generated by passing the current through the first wiring and passed through the first magnetic film can efficiently be applied to the magnetic recording layer. As a result, information can be written even when an amount of a current passed through the first wiring is small, and power consumption required for writing the information can be reduced.

Moreover, when the magnetoresistance effect film has the first and second nonmagnetic layers, the magnetic film providing the flux path can also be magnetically connected to the magnetic recording layer by the following structure. That is, the width of the first magnetization pinned layer, first nonmagnetic layer and magnetic recording layer is reduced, and set to be not more than the distance between the surfaces of the first and second portions facing to each other. In this case, when the magnetic recording layer is positioned between the first and second portions, the magnetic film can be magnetically connected to the magnetic recording layer. Therefore, the information can be written even when the amount of the current

passed through the first wiring is small, and the power consumption required for writing the information can be reduced.

In the first to fourth aspects of the present invention, a length of the first magnetic film along a longitudinal direction of the first wiring may be 1.2 times or more, or 1.5 times or more the length of the magnetoresistance effect film along the longitudinal direction of the first wiring. Similarly, the length of the second magnetic film along the longitudinal direction of the second wiring may be 1.2 times or more, or 1.5 times or more the length of the magnetoresistance effect film along the longitudinal direction of the second wiring. In this case, the magnetic field can more effectively be applied to the magnetic recording layer.

The first and second wirings may contain one material selected from the group consisting of aluminum, copper, tungsten, and an alloy of these metals. Alternatively, the first and second wirings may have a multilayered structure including the nonmagnetic layer and high saturation magnetization soft magnetic material layer, such as a laminated structure of a Cu layer and CoFeNi layer. When the wirings are made of the material mainly containing Cu and the first and second magnetic films are alloy based films containing Co or Co-Fe as a main component, Cu and Co or Co-Fe are

hardly dissolved in each other. Therefore, even when a usual heat treatment process is performed or an excessively large current is passed, Cu contained in the wiring and Co or Co-Fe contained in the magnetic film are not mutually diffused. Therefore, it is unnecessary to dispose a barrier metal between the wiring and the magnetic film.

Each of the first and second magnetic films can comprise a Co-Fe alloy film, a Co-Fe-Ni alloy film, an amorphous material film such as a Co-(Zr, Hf, Nb, Ta, Ti) film, a (Co, Fe, Ni)-(Si, B) based film, a (Co, Fe, Ni)-(P, Al, Mo, Nb, Mn) based film and a (Co, Fe, Ni)-(Si, B)-(P, Al, Mo, Nb, Mn) based film, and metal-nonmetal nano-granular films such as a (Fe, Co)-(B, Si, Hf, Zr, Sm, Ta, Al)-(F, O, N) based film. In more detail, these magnetic films may also comprise the high saturation magnetization soft magnetic material film containing a Co element, or the metal-nonmetal nano-granular films such as a (Fe, Co)-(B, Si, Hf, Zr, Sm, Ta, Al)-(F, O, N) based film.

It is noted that the metal-nonmetal nano-granular film may have a structure in which metal granules are dispersed in a nonmetal matrix. Alternatively, the metal-nonmetal nano-granular film may have a structure in which nonmetal granules are dispersed in a metal matrix.

The magnetization pinned layer and magnetic

recording layer may contain Fe, Co, Ni, an alloy of these metals, and half metals such as NiMnSb, PtMnSb and Co₂MnGe. A saturation magnetization B_s of the magnetic recording layer may be more than 5 kG.

5 Moreover, examples of the material of the nonmagnetic tunnel layer include Al₂O₃, AlN, MgO, SiO₂, GaO, LaAlO₃, MgF₂, and CaF₂.

10 In the first to fourth aspects of the present invention, a magnetic film similar to the magnetic film around the first wiring may also be provided around the second wiring. Moreover, the magnetic film in the position of the ferromagnetic tunnel junction may also be extended over the whole wiring.

15 In the first to fourth aspects of the present invention, with respect to a size in a cross-section vertical to the longitudinal direction of the wiring around which the magnetic film is provided, assuming that the length of the magnetic film in an opening width direction is l_1 , and the length thereof in a vertical direction is l_2 , an aspect ratio l_2/l_1 may be larger than 1. In this case, the current magnetic field is strengthened. This aspect ratio l_2/l_1 may be larger than 1.5 and smaller than 5, or else, larger than 2 and smaller than 5.

25 The magnetic memory of the first to fourth aspects of the present invention can further comprise a sense current control device configured to control a sense

current passed through the magnetic memory in order to read the information stored in the magnetic memory. As the sense current control device, a transistor or a diode can be used.

5 BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

FIG. 1A is a sectional view schematically showing a magnetic memory according to a first embodiment of the present invention;

10 FIG. 1B is a partial sectional view taken along a line 1B-1B of the magnetic memory shown in FIG. 1A;

FIG. 1C is an enlarged sectional view of the structure shown in FIG. 1B;

FIG. 1D is a perspective view schematically showing a part of the magnetic memory shown in FIG. 1A;

15 FIGS. 2A and 2B are sectional views schematically showing modification examples of the structure shown in FIGS. 1A to 1D;

20 FIG. 3 is a graph showing a relation between a ratio L_2/L_1 of a magnetic film length L_2 to a magnetoresistance effect film length L_1 and a magnetic field strength H_x ;

FIG. 4 is a circuit diagram showing one example of a circuit constitution of the magnetic memory according to the first embodiment of the present invention;

25 FIG. 5 is a circuit diagram showing another example of the circuit constitution of the magnetic memory according to the first embodiment of the present

invention;

FIG. 6 is a perspective view schematically showing one example of a structure of a magnetic memory in which the circuit constitution shown in FIG. 5 is

5 employed;

FIG. 7A is a sectional view schematically showing the magnetic memory according to a second embodiment of the present invention;

FIG. 7B is a partial sectional view taken along a
10 line 7B-7B of the magnetic memory shown in FIG. 7A;

FIG. 8A is a sectional view schematically showing the magnetic memory according to a third embodiment of the present invention;

FIG. 8B is a partial sectional view taken along a
15 line 8B-8B of the magnetic memory shown in FIG. 8A;

FIG. 9A is a sectional view schematically showing the magnetic memory according to a fourth embodiment of the present invention;

FIG. 9B is a partial sectional view taken along a
20 line 9B-9B of the magnetic memory shown in FIG. 9A;

FIG. 10 is a sectional view schematically showing a part of the magnetic memory according to a fifth embodiment of the present invention;

FIG. 11 is a sectional view schematically showing
25 a part of the magnetic memory according to a sixth embodiment of the present invention;

FIG. 12 is a sectional view schematically showing

a part of the magnetic memory according to a seventh embodiment of the present invention;

5 FIG. 13A is a sectional view schematically showing the magnetic memory according to an eighth embodiment of the present invention;

 FIG. 13B is a partial sectional view taken along a line 13B-13B of the magnetic memory shown in FIG. 13A;

10 FIGS. 14A and 14B are sectional views schematically showing structure examples of a wiring and magnetic film of the magnetic memory according to the eighth embodiment of the present invention;

15 FIGS. 15A to 15C are sectional views schematically showing structure examples of the wiring and magnetic film of the magnetic memory according to the eighth embodiment of the present invention; and

 FIG. 16 is a sectional view schematically showing a part of the magnetic memory according to a ninth embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

20 Embodiments of the present invention will be described in detail below with reference to the accompanying drawings. The same reference numerals denote the same parts in the drawing, and a duplicate explanation will be omitted.

25 FIG. 1A is a sectional view schematically showing a magnetic memory according to a first embodiment of the present invention. FIG. 1B is a partial sectional

view taken along a line 1B-1B of the magnetic memory shown in FIG. 1A, and FIG. 1C is an enlarged sectional view of a structure shown in FIG. 1B. Moreover, FIG. 1D is a perspective view schematically showing a part of the magnetic memory shown in FIG. 1A.

A magnetic memory 10 shown in FIGS. 1A to 1D is a magnetic random access memory (MRAM), and is, as shown in FIG. 1A, mainly constituted by a magnetic memory 11 and a transistor 12 as a sense current control device for controlling a sense current to be passed through the magnetic memory 11.

The magnetic memory 11 has a ferromagnetic double tunnel junction 13. The ferromagnetic double tunnel junction 13 is positioned between wirings 14, 15 crossing at right angles to each other, and a lower end of the tunnel junction is connected to the transistor 12 via a wiring 16. Moreover, magnetic films 17, 18 are provided around the wirings 14, 15, respectively. Furthermore, in the first embodiment, the magnetic film 18 is made of a high saturation magnetization soft magnetic material. It is noted that a reference numeral 19 denotes an interlayer insulating film, 20 denotes a substrate, and a double-arrow 26 denotes an axis of easy magnetization.

The ferromagnetic double tunnel junction 13 has a structure in which a magnetization pinned layer 21, tunnel barrier layer 22, magnetic recording layer 23,

tunnel barrier layer 24, and magnetization pinned layer 25 are laminated in the order noted above from a wiring 16 side. A width of the magnetization pinned layer 25 is smaller than that of the magnetization pinned layer 21, tunnel barrier layer 22, magnetic recording layer 23, and tunnel barrier layer 24, and upper surfaces of the tunnel barrier layer 24 positioned on opposite sides of the wiring 15 are exposed. Both ends of the magnetic film 18 opened on a magnetization pinned layer 25 side contact the exposed upper surfaces of the tunnel barrier layer 24, respectively. That is, the magnetic film 18 is magnetically connected to the tunnel barrier layer 24, and to the magnetic recording layer 23 via the tunnel barrier layer 24.

When the magnetic film 18 is in contact with the magnetization pinned layer 25, the magnetic film 18 is magnetically connected to the magnetization pinned layer 25. Therefore, a current magnetic field cannot effectively act on the magnetic recording layer 23. On the other hand, in the structure shown in FIG. 1C, since the magnetic film 18 is connected to the magnetic recording layer 23 only via the tunnel barrier layer 24, the current magnetic field can effectively act on the magnetic recording layer 23.

It is noted that, with this structure, reduction of power consumption to about 1/5 or less has been confirmed. It is also noted that, a principle for

reducing the power consumption has been described only for the magnetic film 18, but this principle also can be applied to the magnetic film 17.

5 Instead of the structure described with reference to FIGS. 1A to 1D, structures shown in FIGS. 2A and 2B may also be employed.

FIGS. 2A and 2B are sectional views schematically showing modification examples of the structure shown in FIGS. 1A to 1D.

10 In the magnetic memory 10 shown in FIG. 2A, the width of the magnetization pinned layer 25 is smaller than an opening width of the magnetic film 18, and the magnetization pinned layer 25 is positioned between sidewall portions of the magnetic film 18. In this
15 structure, the current magnetic field can also effectively act on the magnetic recording layer 23.

In the magnetic memory 10 shown in FIG. 2B, the width of the magnetization pinned layer 25 is smaller than the opening width of the magnetic film 18, and the
20 magnetic recording layer 23 is positioned between the sidewall portions of the magnetic film 18. In this structure, the current magnetic field can also effectively act on the magnetic recording layer 23. Moreover, according to the structure, the magnetic
25 recording layer 23 is positioned between the sidewall portions of the magnetic film 18. Therefore, when a writing magnetic field is applied to one of two storage

cells adjacent to each other, an influence of the writing magnetic field onto the magnetic recording layer 23 of the other cell is reduced. Therefore, according to the structure shown in FIG. 2B, not only
5 the reduction of the power consumption on writing is achieved but also cross talk can more effectively be prevented.

In the first embodiment, a saturation magnetization B_s of the high saturation magnetization soft magnetic material for use in the magnetic films 17,
10 18 is preferably larger than 5 kG. When the saturation magnetization B_s is larger than 5 kG, the effect of reducing the power consumption conspicuously appears.

Moreover, the length of the magnetic film 17 along
15 the longitudinal direction of the wiring 14 is preferably more than the length of the magnetoresistance effect film 13 along the longitudinal direction of the wiring 14. This respect will be described with reference to FIG. 3.

20 FIG. 3 is a graph showing a relation between a ratio L_2/L_1 of a length L_2 of the magnetic film 17 along the longitudinal direction of the wiring 14 to a length L_1 of the magnetoresistance effect film 13 along the longitudinal direction of the wiring 14, and a
25 magnetic field strength H_x in a position of the magnetic recording layer 23. Note that the graph is obtained by simulation. In FIG. 3, the abscissa

denotes the ratio L_2/L_1 , and the ordinate denotes the magnetic field strength H_x .

As shown in FIG. 3, when the ratio L_2/L_1 is larger, a higher magnetic field strength H_x is obtained.

5 Moreover, when the ratio L_2/L_1 increases to a certain degree, a rise of the magnetic field strength H_x tends to be saturated. In order to more effectively apply the magnetic field to the magnetic recording layer 23, the ratio L_2/L_1 is preferably 1.2 or more, more
10 preferably 1.5 or more. Similarly, a ratio L_4/L_3 of a length L_4 of the magnetic film 18 along the longitudinal direction of the wiring 15 to a length L_3 of the magnetoresistance effect film 13 along the longitudinal direction of the wiring 15 is preferably
15 1.2 or more, more preferably 1.5 or more. In this case, the magnetic field can more effectively be applied to the magnetic recording layer 23, and the effect of reducing the power consumption becomes more conspicuous.

The magnetic film 18 preferably contacts the
20 tunnel barrier layer 24. However, if the magnetic film 18 is magnetically connected to the tunnel barrier layer 24, and magnetic connection of the magnetic film 18 to the magnetic recording layer 23 is thereby
25 achieved, the magnetic film 18 may not contact the tunnel barrier layer 24. Such magnetic connection is realized when a distance between the magnetic film 18 and the tunnel barrier layer 24 is $0.1 \mu\text{m}$ or less,

preferably 0.05 μm or less.

Moreover, since a writing time is as short as several nanoseconds (i.e., the memory is used at a high frequency), a skin depth δ is preferably a sub-micron or more. It is noted that the skin depth δ , specific resistance ρ , frequency ω , and permeability μ have a relation as represented by the following equation:

$$\delta = (2\rho/\omega\mu)^{1/2}$$

Therefore, the specific resistance of the high saturation magnetization soft magnetic material is preferably 20 $\mu\Omega\cdot\text{cm}$ or more, and more preferably 50 $\mu\Omega\cdot\text{cm}$ or more.

Each of the magnetic films 17, 18 containing the high saturation magnetization soft magnetic material can be constituted by an alloy film such as a Co-Fe alloy film and a Co-Fe-Ni alloy film; an amorphous material film such as a Co-(Zr, Hf, Nb, Ta, Ti) film and a (Co, Fe, Ni)-(Si, B)-(P, Al, Mo, Nb, Mn) based film; and a metal-nonmetal nano-granular film such as a (Fe, Co)-(B, Si, Hf, Zr, Sm, Ta, Al)-(F, O, N) based film. When these materials are used, and a ratio of constituting elements is appropriately adjusted, a magnetostriction can be set substantially to zero, and the softened magnetic films 17, 18 having a small coercive force can be obtained. Note that sectional shapes of the magnetic films 17, 18 are not limited to those shown in FIGS. 1A to 1D, and various modified

shapes can be used.

A cobalt-based alloy containing cobalt as a main component is preferably used as the high saturation magnetization soft magnetic material contained in the magnetic films 17, 18, and a material containing copper as a main component for a high current density is preferably used as the material of the wirings 14, 15. In this case, these constituting materials can be prevented from being mutually diffused between the wirings 14, 15 and magnetic films 17, 18. Therefore, a thermal stability is enhanced, and a deterioration with an elapse of time can be suppressed.

The magnetization pinned layers 21, 25 may be constituted by ferromagnetic layers. The material constituting the ferromagnetic layer is not particularly limited as long as a ferromagnetic property is exhibited. Examples of the material include: metals such as Fe, Co and Ni; alloys of these metals; oxides such as a magnetite having a large spin polarization ratio (Fe_3O_4), CrO_2 , and RXMnO_{3-y} (R represents a rare earth element, and X represents at least one element of Ca, Ba, and Sr); and Heusler's alloys such as NiMnSb and PtMnSb . The ferromagnetic layer needs to be thick to such an extent that superparamagnetism is not provided, and is preferably 0.4 nm thick or more.

It is preferable to laminate an antiferromagnetic

film of Fe-Mn, Pt-Mn, Pt-Cr-Mn, Ni-Mn, Ir-Mn, NiO,
and Fe₂O₃ on the ferromagnetic layer, and fix a
magnetization direction. Moreover, a laminated film of
the ferromagnetic and nonmagnetic layers may be used as
5 the magnetization pinned layers 21, 25. When a three-
layer film of a ferromagnetic layer/nonmagnetic
layer/ferromagnetic layer is used as the laminated film,
it is preferable to generate an antiferromagnetic
interaction between the ferromagnetic layers via the
10 nonmagnetic layer.

Particularly, in a structure in which an
antiferromagnetic film made of Fe-Mn, Pt-Mn, Pt-Cr-Mn,
Ni-Mn, Ir-Mn, NiO, and Fe₂O₃ is formed on the
ferromagnetic film via laminated films such as
15 Co(Co-Fe)/Ru/Co(Co-Fe) and Co(Co-Fe)/Ir/Co(Co-Fe), the
magnetization direction of the magnetization pinned
layers 21, 25 is hardly influenced by the current
magnetic field. That is, the magnetization direction
of the ferromagnetic layer can firmly be fixed.

20 A ratio L/W of a length L and width W of the
magnetic recording layer 23 is preferably 1.5 or more,
more preferably 2 or more. However, with the structure
shown in FIGS. 1A to 1D, even when the ratio L/W is 1,
a high density can be realized by a single magnetic
25 domain. Moreover, uniaxial anisotropy is preferably
imparted to the magnetic recording layer 23 in a length
direction of the layer, and both ends of the layer in

the length direction (a direction of magnetization easy axis) are preferably connected to the magnetic film 18 via the tunnel barrier layer 24.

5 The material for use in the magnetic recording layer 23 is not particularly limited as long as the ferromagnetic property is exhibited. Examples of the material include: metals such as Fe, Co and Ni; alloys of these metals; oxides such as a magnetite having a large spin polarization ratio (Fe_3O_4), CrO_2 , and
10 RXMnO_{3-y} (R represents a rare earth element, and X represents at least one element of Ca, Ba, and Sr); and Heusler's alloys such as NiMnSb and PtMnSb . The ferromagnetic layer needs to be thick to such an extent that super-paramagnetism is not provided, and is
15 preferably 0.4 nm thick or more.

The magnetic recording layer 23 may be of a single layer structure or a laminated structure. When the magnetic recording layer 23 has the laminated structure, for example, a two-layer film of a soft ferromagnetic
20 layer/ferromagnetic layer or a three-layer film of a ferromagnetic layer/soft ferromagnetic layer/ferromagnetic layer may be used.

Moreover, another structure can also be employed in which the magnetic recording layer 23 is a three-
25 layer film of a ferromagnetic layer/nonmagnetic layer/ferromagnetic layer, and these ferromagnetic layers mutually interact in an antiferromagnetic or

weakly ferromagnetic manner via the nonmagnetic layer.

In this case, when the current magnetic field acts on the magnetic recording layer 23, an influence of stray field to the magnetization pinned layers 21, 25 from the magnetic recording layer 23 is eliminated.

Additionally, even when a memory cell width is set to be a sub-micron or less, increase of power consumption necessary for generating a predetermined current magnetic field by diamagnetism can be suppressed. When this structure is employed, it is preferable that a softer layer is used in the ferromagnetic layer on a magnetic film 18 side, or the film thickness of the layer is set to be larger. Similarly as described above, a two-layer film of a soft ferromagnetic layer/ferromagnetic layer, or a three-layer film of a ferromagnetic layer/soft ferromagnetic layer/ferromagnetic layer can be used as the soft layer.

In addition to the aforementioned magnetic materials, the ferromagnetic layer for use in the magnetization pinned layers 21, 25 and magnetic recording layer 23 can contain nonmagnetic elements such as Ag, Cu, Au, Al, Mg, Si, Bi, Ta, B, C, O, N, Pd, Pt, Zr, Ir, W, Mo, and Nb in a range in which the ferromagnetic property is not lost. Moreover, the ferromagnetic layer for use in the magnetization pinned layers 21, 25 preferably has a unidirectional anisotropy parallel to the film surface, and the

ferromagnetic layer for use in the magnetic recording layer 23 preferably has uniaxial anisotropy parallel to the film surface. The thickness of the ferromagnetic layer is preferably in a range of 0.1 nm to 100 nm, and is preferably smaller. When the magnetic memory 10 is prepared, the thickness of the ferromagnetic layer is preferably 10 nm or less.

As the material of the tunnel barrier layers 22, 24, dielectric materials or insulating materials such as Al_2O_3 , AlN , MgO , SiO_2 , MgO , LaAlO_3 , MgF_2 , CaF_2 , SrTiO_2 , and AlLaO_3 can be used. Omission of oxygen, nitrogen, or fluorine may exist in these materials.

The magnetic memory 10 can be formed on the substrate 20 in a surface region of which at least a part of the transistor 12, and the like are formed. The material of the substrate 20 is not especially limited, and Si , SiO_2 , Al_2O_3 , spinel, AlN , and the like can be used. Moreover, the magnetic memory 10 is preferably formed on the substrate via a protective layer or a underlayer. Examples of the material for use in the protective layer or the underlayer include Ta , Ti , Pt , Pd , Au , Ti/Pt , Ta/Pt , Ti/Pd , Ta/Pd , Cu , Al-Cu , W , and the like.

The magnetic memory 10 can be manufactured using usual thin film forming techniques such as various sputtering processes, evaporation process, and molecular beam epitaxy process.

A circuit diagram of the aforementioned magnetic memory 10 is shown in FIG. 4.

FIG. 4 is a circuit diagram showing one example of a circuit constitution of the magnetic memory 10 according to the first embodiment of the present invention. In FIG. 4, the wiring 15 of the magnetic memory 10 shown in FIGS. 1A to 1D is used as a bit line, and the wiring 14 is used as a word line. Moreover, in FIG. 4, reference numeral 27 denotes a word line, 28 denotes a bit line, 29 denotes a row decoder, 30 denotes a column decoder, and 31 denotes a sense amplifier. The magnetic memory 10 shown in FIGS. 1A to 1D can take, for example, this circuit constitution.

When the magnetic memory 11 shown in FIGS. 1A to 1D is used, the magnetic memory can be realized even with the circuit constitution shown in FIG. 5.

FIG. 5 is a circuit diagram showing another example of the circuit constitution of the magnetic memory 10 according to the first embodiment of the present invention. Moreover, FIG. 6 is a perspective view schematically showing one example of the structure of the magnetic memory 11 in which the circuit constitution shown in FIG. 5 is employed. As shown in FIGS. 5 and 6, the ferromagnetic double tunnel junction 13 and diode 32 are connected in series with each other, and are connected to an intersection of the word line 14 and bit line 15. This structure can also be

employed.

A second embodiment of the present invention will next be described.

FIG. 7A is a sectional view schematically showing the magnetic memory according to the second embodiment of the present invention, and FIG. 7B is a partial sectional view taken along a line 7B-7B of the magnetic memory shown in FIG. 7A. Different from the magnetic memory 10 of the first embodiment, in the magnetic memory 10 of the second embodiment, the magnetic films 17, 18 are formed not only in the position of the ferromagnetic double tunnel junction 13 but also over the whole wirings 14, 15. When this structure is employed, the magnetic films 17, 18 are easily aligned with the ferromagnetic double tunnel junction 13.

A third embodiment of the present invention will next be described.

FIG. 8A is a sectional view schematically showing the magnetic memory according to the third embodiment of the present invention, and FIG. 8B is a partial sectional view taken along a line 8B-8B of the magnetic memory shown in FIG. 8A. Different from the magnetic memory 10 of the first embodiment, in the magnetic memory 10 according to the third embodiment, the magnetic film 17 is disposed not only below but also above the wiring 16. When the structure is employed, the current magnetic field from the wiring 14 can more

efficiently act on the ferromagnetic double tunnel junction 13.

A fourth embodiment of the present invention will next be described.

5 FIG. 9A is a sectional view schematically showing the magnetic memory according to the fourth embodiment of the present invention, and FIG. 9B is a partial sectional view taken along a line 9B-9B of the magnetic memory shown in FIG. 9A. In the magnetic memory 10 according to the fourth embodiment, different from the magnetic memory 10 of the first embodiment, the magnetic films 17, 18 are formed not only in the position of the magnetic recording layer 23 but also over the whole wirings 14, 15. When the structure is employed, the magnetic films 17, 18 can easily be aligned with the ferromagnetic double tunnel junction 13. Moreover, in the magnetic memory 10 according to the fourth embodiment, different from the magnetic memory 10 of the first embodiment, the magnetic film 17 is formed not only below but also above the wiring 16. When the structure is employed, the current magnetic field from the wiring 14 can more efficiently act on the ferromagnetic double tunnel junction 13.

15 A fifth embodiment of the present invention will next be described.

25 FIG. 10 is a sectional view schematically showing a part of the magnetic memory according to the fifth

embodiment of the present invention. In the magnetic memory 10 of the fifth embodiment, different from the magnetic memory 10 according to the first embodiment, the wiring 15 does not directly contact the magnetic film 18, and a dielectric film or an insulating film 19 is positioned between the wiring and the magnetic film. In this manner, the wiring 15 may electrically contact the magnetic film 18, or may not contact the film.

A sixth embodiment of the present invention will next be described.

FIG. 11 is a sectional view schematically showing a part of the magnetic memory according to the sixth embodiment of the present invention. In the magnetic memory 10 according to the first to fifth embodiments, the wiring 15 serving as both the current wiring and the bit line is used. On the other hand, in the magnetic memory 10 according to the sixth embodiment, a current wiring 33 and bit line 34 are provided independently from each other. When the aforementioned principle is utilized, the current magnetic field can efficiently act on the ferromagnetic double tunnel junction 13, and therefore this structure is also possible.

In the aforementioned first to sixth embodiments, the width of the magnetization pinned layer 25 is set to be smaller than the width of the magnetization pinned layer 21, tunnel barrier layer 22, magnetic

recording layer 23, and tunnel barrier layer 24, the upper surfaces of the tunnel barrier layer 24 facing the sidewall parts of the magnetic film 18 are exposed, and the exposed surfaces are utilized to magnetically connect the magnetic film 18 to the magnetic recording layer 23. On the other hand, in the following seventh embodiment, all the magnetization pinned layer 21, tunnel barrier layer 22, magnetic recording layer 23, tunnel barrier layer 24, and magnetization pinned layer 25 are formed to have the same width.

FIG. 12 is a sectional view schematically showing a part of the magnetic memory according to the seventh embodiment of the present invention. In the magnetic memory 10 of the seventh embodiment, different from the magnetic memory 10 according to the first embodiment, all the magnetization pinned layer 21, tunnel barrier layer 22, magnetic recording layer 23, tunnel barrier layer 24, and magnetization pinned layer 25 are formed to have the same width. Therefore, in a method similar to that of the first to sixth embodiments, the magnetic film 18 cannot magnetically be connected to the magnetic recording layer 23.

To solve the problem, in the seventh embodiment, the opening width of the magnetic film 18 is set to be not less than the width of the ferromagnetic double tunnel junction 13. According to this structure, since the magnetization pinned layer 25 is not disposed

between each end of the magnetic film 18 and the magnetic recording layer 23, the magnetic connection of the magnetic film 18 to the magnetic recording layer 23 is not inhibited by the magnetization pinned layer 25.

5 Therefore, according to the seventh embodiment, the current magnetic field can efficiently act on the magnetic recording layer, and the power consumption required for writing the information can be reduced.

10 In the seventh embodiment, the distance between the opposite ends of the magnetic film 18 and the magnetic recording layer 23 is not especially limited as long as the magnetic connection of the magnetic film 18 to the magnetic recording layer 23 is achieved, but the closer distance is preferable. Usually, the
15 distance between the opposite ends of the magnetic film 18 and the magnetic recording layer 23 is sufficiently 0.05 μm or less.

An eighth embodiment of the present invention will next be described.

20 FIG. 13A is a sectional view schematically showing the magnetic memory according to the eighth embodiment of the present invention, and FIG. 13B is a partial sectional view taken along a line 13B-13B of the magnetic memory shown in FIG. 13A. The magnetic memory
25 10 of the eighth embodiment is different from the magnetic memory 10 of the seventh embodiment in that the magnetic film 17 is formed not on a side surface of

the wiring 14, but only on a bottom surface of the wiring.

When the CMOS transistor 12 is used as a sense current control device, and when the width of the ferromagnetic double tunnel junction 13 (size in a direction parallel to the bit line 15) is W, and length (size in a direction parallel to the word line 14) is L, the distance between the adjacent ferromagnetic double tunnel junctions 13 in the longitudinal direction of the wiring 14 is usually substantially the same as the width W. On the other hand, the distance between the ferromagnetic double tunnel junctions 13 adjacent to each other in the longitudinal direction of the wiring 15 is substantially three times the width W. That is, in the magnetic memory, the distance between the ferromagnetic double tunnel junctions 13 adjacent to each other is relatively short in the width direction, but sufficiently long in the length direction.

Therefore, the cross talk between the ferromagnetic double tunnel junctions 13 adjacent to each other in the longitudinal direction of the wiring 14 needs to be considered, but the cross talk between the ferromagnetic double tunnel junctions 13 adjacent to each other in the longitudinal direction of the wiring 15 does not necessarily have to be considered. Therefore, in this case, as shown in FIGS. 13A, 13B, the magnetic film 18 is formed on the side and bottom

surfaces of the wiring 15, and the magnetic film 17 is not formed on the side surface of the wiring 14 but is formed only on the bottom surface of the wiring. Then, the current magnetic field can efficiently act on the ferromagnetic double tunnel junction 13 without causing the cross talk.

In the magnetic memory shown in FIGS. 13A and 13B, in order to more efficiently allow the current magnetic field to act on the ferromagnetic double tunnel junction 13, structures shown in FIGS. 14A, 14B and FIGS. 15A to 15C may be employed.

FIGS. 14A and 14B are sectional views schematically showing a structure example of the wiring 14 and magnetic film 17 of the magnetic memory according to the eighth embodiment of the present invention. Moreover, FIGS. 15A to 15C are sectional views schematically showing the structure example of the wiring 15 and magnetic film 18 of the magnetic memory according to the eighth embodiment of the present invention.

In FIG. 14A and FIGS. 15A and 15C, a combination of the wiring 14 and the magnetic film 17, and a combination of the wiring 15 and the magnetic film 18 constitute two-layer structures. Moreover, in FIG. 14B and FIG. 15B, a combination of the wiring 14 and the magnetic film 17, and a combination of the wiring 15 and the magnetic film 18 constitute three-layer

structures. When the combination of the wiring and the magnetic film constitutes a multiple-layer structure in this manner, as compared with the single-layer structure, the current magnetic field can more efficiently act on the ferromagnetic double tunnel junction 13.

In the aforementioned first to eighth embodiments, the reduction of the writing power consumption by the predetermined structure in the magnetic memory having the ferromagnetic double tunnel junction has been described. In the following ninth embodiment, when the magnetic film made of a predetermined material is used, the power consumption during writing of the magnetic memory having a ferromagnetic single tunnel junction is reduced.

FIG. 16 is a sectional view schematically showing a part of the magnetic memory according to the ninth embodiment of the present invention. The magnetic memory 10 of the ninth embodiment has a structure similar to that of the magnetic memory 10 of the first embodiment. That is, the magnetic memory 10 of the ninth embodiment has a ferromagnetic single tunnel junction 35 in which the magnetization pinned layer 21, tunnel barrier layer 22, and magnetic recording layer 23 are successively laminated. The bit line 34 is formed on the ferromagnetic single tunnel junction 35. The current wiring 33 coated with the magnetic film 18

is formed on the bit line 34 via the insulating film 19. It is noted that, below the ferromagnetic single tunnel junction 35, a wiring is disposed crossing at right angles to the current wiring 33 and bit line 34, and
5 the magnetic film is also formed on such wiring.

In the ninth embodiment, the magnetic film 18 is constituted by the high saturation magnetization soft magnetic material film containing a Co element or the metal-nonmetal nano-granular film. When this thin film
10 is used, the power consumption necessary for writing the information into the magnetic recording layer 23 can be reduced.

Examples of the high saturation magnetization soft magnetic material film containing the Co element and
15 constituting the magnetic film 18 include: alloy film such as a Co-Fe alloy film and Co-Fe-Ni alloy film; and amorphous material film such as a Co-(Zr, Hf, Nb, Ta, Ti) film and a (Co, Fe, Ni)-(Si, B)-(P, Al, Mo, Nb, Mn) based film. Moreover, examples of the metal-nonmetal
20 nano-granular film constituting the magnetic film 18 include: a (Fe, Co)-(B, Si, Hf, Zr, Sm, Ta, Al)-(F, O, N) based metal-nonmetal nano-granular film. When these materials are used, and the ratio of the constituting
25 elements is appropriately adjusted, the magnetostriction can be set substantially to zero, and the softened magnetic film 18 having a small coercive force can be obtained.

In the ninth embodiment, the reduction of the power consumption for writing the information into the magnetic memory having the ferromagnetic single tunnel junction by the magnetic film made of the predetermined material has been described. However, with the material, the writing power consumption can of course be reduced even in the magnetic memory having the ferromagnetic double tunnel junction. Moreover, in the first to ninth embodiments, the magnetic films are formed on both the pair of wirings intersecting each other via the ferromagnetic tunnel junction, but the magnetic film may be formed on only one of the wirings. In this case, the power consumption on writing can also be reduced.

Examples of the present invention will be described hereinafter.

(Example 1)

The magnetic memory 10 shown in FIG. 16 was formed in the following method.

First, a Ta underlayer and a 50 nm thick Cu layer were successively laminated on an Si/SiO₂ substrate (not shown). Subsequently, successively formed on the Cu layer were a composite film for use as the magnetization pinned layer 21 of a 2 nm thick Ni₈₁Fe₁₉ layer, 12 nm thick Ir₂₂Mn₇₈ layer, and 3 nm thick Co₅₀Fe₅₀ layer; a 1 nm thick Al₂O₃ layer for use as the tunnel barrier layer 22; a composite film for use as

the magnetic recording layer 23 of a 3 nm thick $\text{Co}_{50}\text{Fe}_{50}$ layer and 5 nm thick Ta layer; and an Au layer for use as the protective film (not shown).

5 It is noted that a sputtering process or an evaporation process was used in forming these thin films, and an initial vacuum degree was 3×10^{-8} Torr. Moreover, the Al_2O_3 layer was formed by using Al target as a sputtering target, and introducing a pure Ar gas as a sputtering gas to form the film in vacuum, and
10 exposing the Al film to plasma oxygen. In this method, the thin Al_2O_3 layer was formed without any omission of oxygen.

Subsequently, the laminated film (including the Au layer to the $\text{Ni}_{81}\text{Fe}_{19}$ layer on the Cu layer) formed by
15 the aforementioned method was patterned in a size of $4 \mu\text{m} \times 16 \mu\text{m}$ using photolithography and ion milling techniques. The ferromagnetic tunnel junction 35 was formed as described above.

Subsequently, while the resist pattern utilized in
20 the patterning was left as it was, the 250 nm thick Al_2O_3 layer was formed as the interlayer insulating film 19 by an electron beam evaporation. Thereafter, the resist pattern was lifted off, and a resist pattern was further formed in order to form the wiring 34.
25 After the surface was cleaned by sputtering, the Cu wiring 34 was formed.

Subsequently, the 250 nm thick interlayer

insulating film 19 of SiO_2 was formed by a reactive sputtering process, and the Au wiring 33 was formed by lifted-off process,. Thereafter, the high saturation magnetization soft magnetic material was sputtered, the
5 resulting thin film was patterned in the ion milling process, and the magnetic film 18 was obtained. As described above, the magnetic memory 10 shown in FIG. 16 was formed and thereafter treated in a heat treatment furnace in the magnetic field. As a result,
10 the uniaxial anisotropy was imparted to the magnetic recording layer 23 and the unidirectional anisotropy was imparted to the magnetization pinned layer 21.

It is noted that a plurality of types of magnetic memories 10 were manufactured using materials shown
15 in the following table 1 as the high saturation magnetization soft magnetic material. Moreover, for comparison, a magnetic memory with no magnetic film 18 formed thereon, and a magnetic memory using a high permeability material Ni-Fe in the magnetic film 18
20 were also manufactured.

The power consumption of the magnetic memory 10 manufactured in the aforementioned method was measured in the following method. That is, when a current pulse of 10 nsec was passed through the wiring 33, the
25 current magnetic field was exerted onto the magnetic recording layer 23 in the easy axis direction 26. Moreover, in a magnetically hard axis direction, a

magnetic field of 20 Oe was exerted using a Helmholtz coil. A current value of current pulse was gradually increased, and a current I_c at which the magnetization of the magnetic recording layer 23 was reversed was recorded. It is noted that, whether or not the magnetization of the magnetic recording layer 23 was reversed was judged by passing a direct current through the ferromagnetic single tunnel junction 35 and observing a change of output voltage. Results are also shown in the following table 1.

Table 1

Material of magnetic film	Ic(mA)
Co ₉₀ Fe ₁₀	16
Co ₆₀ Fe ₂₀ Ni ₂₀	14
Co ₃₀ Fe ₃₀ Ni ₄₀	15
Co _{70.3} Fe _{4.7} Si ₁₅ B ₁₀	13
Co _{75.3} Fe _{4.7} Si ₄ B ₁₆	13
Co _{69.6} Fe _{4.6} Mo _{1.8} Si ₈ B ₁₅	13
Co ₇₀ Mn ₆ B ₂₄	14
Co _{81.5} Mo _{9.5} Zr ₉	15
Co ₉₆ Zr ₄	13
Co ₈₇ Nb ₅ Zr ₈	14
Co ₈₅ Nb _{7.5} Ti _{7.5}	14
Co ₉₀ Fe ₂ Nb ₈	13
Co ₆₀ Al ₁₀ O ₃₄	14
Fe ₅₈ V ₁₃ O ₂₉	16
Fe ₄₉ Al ₁₇ O ₃₄	16
Fe ₄₀ B ₂₅ N ₃₅	15
Fe ₅₉ Sm ₁₇ O ₂₄	17
absent	45
Ni ₈₁ Fe ₁₉	22
Ni ₆₀ Fe ₄₀	20

As shown in the above table 1, in the magnetic memory 10 of the present example, as compared with the apparatus having no magnetic film 18, Ic is of course low. Even as compared with the use of the high permeability material Ni-Fe in the magnetic film 18, a lower Ic was obtained. That is, it was confirmed that the writing power consumption was reduced in the magnetic memory 10 of the present example.

Moreover, a similar test was carried out for the magnetic memory 10 having the ferromagnetic double tunnel junction 13. As a result, a similar tendency was found as described above.

5 (Example 2)

The magnetic memory 10 shown in FIGS. 1A to 1D was formed in the following method.

10 First, an SiO₂ film was formed on the Si/SiO₂ substrate using a plasma CVD process. Subsequently, a damascene process was used to form the magnetic film 17 and wiring 14 on the SiO₂ film.

15 That is, a stepper was used to form a rectangular recessed portion in the SiO₂ film. Subsequently, the sidewall and bottom surface of the recessed portion were coated by an Ni₄₀Fe₆₀ film sputtered as the high saturation magnetization soft magnetic material. Subsequently, the recessed portion was filled with Cu by a plating process. Thereafter, the CMP method was used to remove the high saturation magnetization soft magnetic material film and Cu film positioned outside the recessed portion, and the magnetic film 17 and wiring 14 were formed.

20 Subsequently, a 250 nm interlayer insulating film of SiO₂ was formed on the surface of the Si/SiO₂ substrate with the magnetic film 17 and wiring 14 formed thereon by the plasma CVD process. A Ta/W/Ta underlayer and 50 nm thick Cu layer were successively

25

laminated on the interlayer insulating film (no shown).
Subsequently, successively formed on the Cu layer were
a composite film for use as the magnetization pinned
layer 21 of a 2 nm thick $\text{Ni}_{81}\text{Fe}_{19}$ layer, 12 nm thick
5 $\text{Ir}_{22}\text{Mn}_{78}$ layer, and 3 nm thick $\text{Co}_{50}\text{Fe}_{50}$ layer; a 1 nm
thick Al_2O_3 layer for use as the tunnel barrier layer
22; a composite film for use as the magnetic recording
layer 23 of a 2 nm thick $\text{Co}_{50}\text{Fe}_{50}$ layer and 5 nm thick
 $\text{Ni}_{81}\text{Fe}_{19}$ layer; a 1.2 nm thick Al_2O_3 layer for use as
10 the tunnel barrier layer 24; a composite film for use
as the magnetization pinned layer 25 of a 3 nm thick
 $\text{Co}_{50}\text{Fe}_{50}$ layer, 12 nm thick $\text{Ir}_{22}\text{Mn}_{78}$ layer, and 5 nm
thick Ta layer; and an Au layer for use as the
protective film (not shown).

15 It is noted that the sputtering process or the
evaporation process was used in forming these thin
films, and the initial vacuum degree was 3×10^{-8} Torr.
Moreover, the Al_2O_3 layer was formed in a method
similar to that of the Example 1.

20 Subsequently, the stepper was used to pattern the
laminated film (including the Au layer to the $\text{Ni}_{81}\text{Fe}_{19}$
layer on the Cu layer) formed in the aforementioned
method in a size of $0.8 \mu\text{m} \times 4 \mu\text{m}$. The ferromagnetic
tunnel junction 35 was formed in this manner.

25 Subsequently, a hard mask of SiO_2 and Si_3N_4 able
to be mutually etched was used to pattern the composite
film for use as the magnetization pinned layer 25 of

the $\text{Co}_{50}\text{Fe}_{50}$ layer, $\text{Ir}_{22}\text{Mn}_{78}$ layer and $\text{Ni}_{81}\text{Fe}_{19}$ layer, and the Au layer for use as the protective film in a size of $0.8\text{ }\mu\text{m} \times 2\text{ }\mu\text{m}$.

5 Thereafter, the interlayer insulating film 19 of SiO_2 was formed by the plasma CVD process, the surface of the film was flatted by the CMP process, and the upper surface of the Si_3N_4 pattern was exposed. Note that the thickness of the SiO_2 interlayer insulating film 19 after the CMP process was set to 250 nm.

10 Subsequently, Si_3N_4 pattern was removed by the RIE process, the concave portion was formed, and the Cu wiring 15 was formed in the concave portion.

 Subsequently, the Si_3N_4 pattern was formed as the hard mask on the SiO_2 interlayer insulating film 19, and a trench for the magnetic film 18 was formed in the SiO_2 interlayer insulating film 19 by the RIE process. Subsequently, a trench structure whose bottom surface was constituted by the tunnel barrier layer 24 was formed. Subsequently, the Si_3N_4 pattern was removed by the RIE process, and the exposed surfaces were plasma-oxidized in order to prevent a short circuit between the magnetic film 18 and the magnetic recording layer 23 and wiring 15. Thereafter, a sputtering apparatus having a high directivity was used to sputter $\text{Ni}_{40}\text{Fe}_{60}$ as the high saturation magnetization soft magnetic material so that the trench formed in the aforementioned method was filled, the obtained thin film was

patterned using the ion milling technique, and the magnetic film 18 was formed.

As described above, the magnetic memory 10 shown in FIGS. 1A to 1D was manufactured, and treated in the magnetic field in the heat treatment furnace. Thereby, the uniaxial anisotropy was imparted to the magnetic recording layer 23, and the unidirectional anisotropy was imparted to the magnetization pinned layers 21, 25.

It is noted that the magnetic memory 10 shown in FIGS. 1A to 1D was formed in a similar method except that the magnetic film 17 was not formed. It is also noted that, for comparison, a magnetic memory in which the structure shown in FIG. 11 was used in the magnetic film 17, ferromagnetic double tunnel junction 13, and magnetic film 18, and a magnetic memory in which the structure shown in FIG. 12 was used in the ferromagnetic double tunnel junction 13 and magnetic film 18 without forming the magnetic film 17 were prepared. In these comparative magnetic memories, the distance between the magnetic films 17, 18 and the magnetic recording layer 23 was set to 0.15 μm .

The power consumption was measured with respect to the respective magnetic memories 10 in the following method. That is, a current pulse of 10 nsec was passed through each of the wirings 14, 15, and the current magnetic fields were exerted onto the magnetic recording layer 23 in a direction of the magnetization

easy axis 26 and in a direction of the magnetization hard axis. It is noted that the current value of the current pulse passed through the wiring 14 was set to 5 mA. It is also noted that the current value of the current pulse passed through the wiring 15 was gradually increased, and the current I_c at which the magnetization of the magnetic recording layer 23 was reversed was recorded. Additionally, whether or not the magnetization of the magnetic recording layer 23 was reversed was judged by writing the information, passing the direct current through the ferromagnetic double tunnel junction 13 and observing the output voltage change. Results are shown in the following table 2.

Table 2

Structure of magnetic storage device	Magnetic film 17	I_c (mA)
FIGS. 1A-1D	Present	3.5
FIGS. 1A-1D	Absent	5.1
FIG. 12	Present	17.5
FIG. 12	Absent	19

As shown in the above table 2, it was confirmed that in the magnetic memory 10 of the present example having the trench structure (with the structure shown in FIGS. 1A to 1D), as compared with the magnetic memory 10 having no trench structure (having the structure shown in FIG. 12) and having a long distance

between the magnetic films 17, 18 and the magnetic recording layer 23, I_c was low, and the power consumption for writing was reduced. Moreover, it was confirmed that in the magnetic memory 10 including the magnetic film 17 and having an increasing magnetic field to be exerted in the magnetically hard axis direction, as compared with the magnetic memory 10 including no magnetic film 17, I_c of the magnetically easy axis direction 26 was small, and the power consumption for writing was further reduced.

(Example 3)

The magnetic memory 10 shown in FIGS. 1A to 1D was prepared in a method similar to the method of Example 2 except that the ferromagnetic double tunnel junction 13 was constituted as shown in the following tables 3 and 4 and the materials shown in the following tables 3 and 4 were used in the magnetic films 17, 18. The power consumption was measured with respect to the magnetic memory 10 prepared as described above in a similar method except that the current value of the current pulse passed through the wiring 14 was set to 3 mA. Results are also shown in the tables 3 and 4.

Table 3

Structure of ferromagnetic double tunnel junction	Material of magnetic film	I _c (mA)
PtMn/CogFe/AlN/Fe ₅₅ Co ₄₅ /AlN/CogFeNi/PtMn (17nm/3nm/2nm/5nm/2.6nm/3nm/19nm)	CogFe10	2.5
	Co70.3Fe4.7Si15B10	2.1
	CogFe2Nb8	2.2
	Co30Fe30Ni40	2
Ir ₂₂ Mn ₇₈ /CoFe/Al ₂ O ₃ /Fe ₁₀ Co ₉₀ /Al ₂ O ₃ /CoFe/Ir ₂₂ Mn ₇₈ (15nm/3nm/1.2nm/3nm/1.4nm/5nm/20nm)	Co69.6Fe4.6Mo1.8Si8B1	1.9
	Co60Al10O34	2.1
	CogFe10	2
	Co69.6Fe4.6Mo1.8Si8B1	2
NiMn/CoFe/SiO ₂ /CoFe/Ni ₈₁ Fe ₁₉ /CoFe/SiO ₂ /CoFe/NiMn (19nm/3nm/1.8nm/2nm/4nm/2nm/2nm/5nm/20nm)	Fe49Al17O34	2.1
	Co60Fe20Ni20	2.4
	Co70.3Fe4.7Si15B10	2.2
	Co85Nb7.5Ti7.5	2.1
Ir ₂₂ Mn ₇₈ /CoFeNi/Al ₂ O ₃ /FeCo ₂ Ni/Al ₂ O ₃ /CoFeNi/Ir ₂₂ Mn ₇₈ (15nm/2nm/1.0nm/5nm/1.2nm/3nm/17nm)	CogFe10	2
	Co75.3Fe4.7Si4B16	1.9
	CogFe2Nb8	1.9
	Co60Fe20Ni20	1.8
Ir ₂₂ Mn ₇₈ /CoFe/Al ₂ O ₃ /FeCo/Ru/Fe ₃ Co ₇ /Al ₂ O ₃ /CoFe/Ir ₂₂ Mn ₇₈ (15nm/2nm/1.0nm/3nm/0.7nm/5nm/1.2nm/3nm/17nm)	Cog6Zr4	1.7
	Fe40B25N35	1.7

Table 4

Structure of ferrromagnetic double tunnel junction	Material of magnetic film	I _c (mA)
Ir ₂₂ Mn ₇₈ /CoFe/Ir/FeCo/Al ₂ O ₃ /FeCo/Ir/FeCo/Ir ₂₂ Mn ₇₈ (15nm/2nm/0.8nm/3nm/1.0nm/3nm/0.8nm/3nm/1.2nm/3nm/0.8nm/3nm/17nm)	Co ₉₀ Fe ₁₀	1.6
	Co _{70.3} Fe _{4.7} Si ₁₅ B ₁₀	1.5
	Co ₈₅ Nb _{7.5} Ti _{7.5}	1.5
Ir ₂₂ Mn ₇₈ /CoFe/Ru/FeCo/Al ₂ O ₃ /FeCo/Ru/FeCo/Al ₂ O ₃ /CoFe/Ir ₂₂ Mn ₇₈ (15nm/2nm/0.7nm/3nm/1.0nm/3nm/0.7nm/5nm/1.2nm/3nm/0.7nm/3nm/17nm)	Co ₃₀ Fe ₃₀ Ni ₄₀	1.7
	Co _{69.6} Fe _{4.6} Mo _{1.8} Si ₈ B ₁₅	1.5
	Fe ₄₉ Al ₁₇ O ₃₄	1.9
Ir ₂₂ Mn ₇₈ /CoFe/Ru/FeCo/Al ₂ O ₃ /FeCo/Ni ₈ Fe ₂ /CoFe/Ru/FeCo/Ni ₈ Fe ₂ /CoFe/Al ₂ O ₃ /CoFe/Ru/FeCo/Ir ₂₂ Mn ₇₈ (12nm/2nm/0.7nm/2nm/1.0nm/2nm/2nm/2nm/0.7nm/2nm/4nm/2nm/1.2nm/3nm/0.7nm/3nm/12nm)	Co ₃₀ Fe ₃₀ Ni ₄₀	1.8
	Co ₇₀ Mn ₆ B ₂₄	1.6
	Co ₆₀ Al ₁₀ O ₃₄	1.7
PtMn/CoFe/Ru/FeCo/Al ₂ O ₃ /FeCo/Ni ₈ Fe ₂ /CoFe/Ru/FeCo/Ni ₈ Fe ₂ /CoFe/Al ₂ O ₃ /CoFe/Ru/FeCo/PtMn (15nm/2nm/0.7nm/2nm/1.0nm/2nm/2nm/2nm/0.7nm/2nm/5nm/2nm/1.2nm/3nm/0.7nm/3nm/17nm)	Co ₉₀ Fe ₁₀	1.4
	Co _{75.3} Fe _{4.7} Si ₄ B ₁₆	1.3
	Fe ₄₀ B ₂₅ N ₃₅	1.4
Ir ₂₂ Mn ₇₈ /CoFe/Ru/FeCo/Al ₂ O ₃ /FeCo/Ni ₄ Fe ₆ /CoFe/Ru/FeCo/Ni ₄ Fe ₆ /CoFe/Al ₂ O ₃ /CoFe/Ru/FeCo/Ir ₂₂ Mn ₇₈ (15nm/2nm/0.7nm/2nm/1.0nm/2nm/3nm/2nm/0.7nm/2nm/4nm/2nm/1.2nm/3nm/0.7nm/3nm/17nm)	Co ₆₀ Fe ₂₀ Ni ₂₀	1.4
	Co ₉₆ Zr ₄	1.3
	Co ₈₅ Nb _{7.5} Ti _{7.5}	1.2

As shown in the above Tables 3 and 4, I_c was sufficiently low in any case, but when the magnetic films 17, 18 were constituted by the high saturation magnetization soft magnetic material film containing the Co element and metal-nonmetal nano-granular film, I_c was especially low, and it has also been seen that the writing power consumption was further reduced. Moreover, it has also been seen that when the three-layer film of the ferromagnetic layer/nonmagnetic layer/ferromagnetic layer was used, and an antiferromagnetic interaction was exerted between the ferromagnetic layers via the nonmagnetic layer, I_c did not increase, and the power consumption was further reduced.

As described above, in the present invention, since the magnetic film is made of the predetermined material, the power consumption necessary for writing the information into the magnetic memory can be reduced. Moreover, since the magnetic film is used and the predetermined structure is employed in the present invention, the power consumption necessary for writing the information can also be reduced even in the magnetic memory having the ferromagnetic double tunnel junction.

That is, according to the present invention, there is provided a magnetic memory in which power consumption on writing is reduced.

Additional advantages and modifications will readily occur to those skilled in the art. Therefore, the invention in its broader aspects is not limited to the specific details and representative embodiments shown and described herein. Accordingly, various
5 modifications may be made without departing from the spirit or scope of the general inventive concept as defined by the appended claims and their equivalents.